Forest Carbon Assessment for the Mendocino National Forest in the Forest Service's Pacific Southwest Region

Alexa Dugan (alexa.dugan@usda.gov),
Duncan McKinley (Duncan.mckinley@usda.gov)
Kayanna Warren (Kayanna.warren@usda.gov)
Bella Gordon (bella.gordon@usda.gov)

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*This document is intended to be a 'living document', and will be updated as new data becomes available.

Contents

1.0 Introduction

Carbon uptake and storage are some of the many ecosystem services provided by forests and grasslands. Through the process of photosynthesis, growing plants remove carbon dioxide (CO_2) from the atmosphere and store it in forest biomass (plant stems, branches, foliage, roots) and much of this organic material is eventually stored in forest soils. This uptake and storage of carbon from the atmosphere helps modulate greenhouse gas (GHG) concentrations in the atmosphere. Estimates of net annual storage of carbon indicate that forests in the United States (U.S.) constitute an important carbon sink, removing more carbon from the atmosphere than they are emitting (Pan *et al.*, 2011a). Forests in the U.S. remove the equivalent of about 12 percent of annual U.S. fossil fuel emissions or about 206 teragrams of carbon after accounting for natural emissions, such as wildfire and decomposition (US EPA, 2015; Hayes *et al.*, 2018).

Forests are dynamic systems that naturally undergo fluctuations in carbon storage and emissions as forests establish and grow, die with age or disturbances, and re-establish and regrow. When trees and other vegetation die, either through natural aging and competition processes or disturbance events (e.g., fires, insects), carbon is transferred from living carbon pools to dead pools, which also release carbon dioxide through decomposition or combustion (fires). Management activities include timber harvests, thinning, and fuel reduction treatments that remove carbon from the forest and transfer a portion to wood products. Carbon can then be stored in commodities (e.g., paper, lumber) for a variable duration ranging from days to many decades or even centuries. In the absence of commercial thinnings, harvests, and fuel reduction treatments, forests will thin naturally from mortality-inducing disturbances or aging, resulting in dead trees decaying and emitting carbon to the atmosphere.

Following disturbances or harvests, forest vegetation often regrows, resulting in the uptake and storage of carbon from the atmosphere. Over the long term, forests regrow and often accumulate the same amount of carbon that was emitted from disturbance or mortality (McKinley *et al.*, 2011). Although disturbances, forest aging, and management are often the primary drivers of forest carbon dynamics in some ecosystems, environmental factors such as atmospheric CO_2 concentrations, climatic variability, and the availability of limiting forest nutrients, such as nitrogen, can also influence forest growth and carbon dynamics (Caspersen *et al.*, 2000; Pan *et al.*, 2009).

The Intergovernmental Panel on Climate Change (IPCC) has summarized the contributions of global human activity sectors to climate change in its Fifth Assessment Report (IPCC, 2014). From 2000 to 2009, forestry and other land uses contributed just 12 percent of human-caused global CO_2 emissions.[1] The forestry sector contribution to GHG emissions has declined over the last decade (FAOSTAT, 2013; IPCC, 2014; Smith *et al.*, 2014). Globally, the largest source of GHG emissions in the forestry sector is deforestation (Pan *et al.*, 2011a; Houghton *et al.*, 2012; IPCC, 2014), defined as the removal of all trees to convert forested land to other land uses that

[1] Fluxes from forestry and other land use (FOLU) activities are dominated by CO_2 emissions. Non-CO_2 greenhouse gas emissions from FOLU are small and mostly due to peat degradation releasing methane and were not included in this estimate.

Box 1. Description of the primary forest carbon models used to conduct this carbon assessment

Carbon Calculation Tool (CCT)

Estimates annual carbon stocks and stock change from 1990 to 2013 by summarizing data from two or more Forest Inventory and Analysis (FIA) survey years. CCT relies on allometric models to convert tree measurements to biomass and carbon.

Forest Carbon Management Framework (ForCaMF)

Integrates FIA data, Landsat-derived maps of disturbance type and severity, and an empirical forest dynamics model, the Forest Vegetation Simulator, to assess the relative impacts of disturbances (harvests, insects, fire, abiotic, disease). ForCaMF estimates how much more carbon (non-soil) would be on each national forest if disturbances from 1990 to 2011 had not occurred.

Integrated Terrestrial Ecosystem Carbon (InTEC) model

A process-based model that integrates FIA data, Landsat-derived disturbance maps, as well as measurements of climate variables, nitrogen deposition, and atmospheric CO_2. InTEC estimates the relative effects of aging, disturbance, regrowth, and other factors including climate, CO_2 fertilization, and nitrogen deposition on carbon accumulation from 1950 to 2011. Carbon stock and stock change estimates reported by InTEC are likely to differ from those reported by CCT because of the different data inputs and modeling processes.

either do not support trees or allow trees to regrow for an indefinite period (IPCC, 2000). However, the United States is experiencing a net increase in forestland in recent decades because of the reversion of agricultural lands back to forest and regrowth of cut forests (Birdsey *et al.*, 2006), a trend expected to continue for at least another decade (Wear *et al.*, 2013; USDA Forest Service, 2016).

In this section, we provide an assessment of the amount of carbon stored on the Mendocino National Forest (NF) and how disturbances, management, and environmental factors have influenced carbon storage. This assessment primarily used two recent U.S. Forest Service reports: the Baseline Report (USDA Forest Service, 2015) and Disturbance Report (Birdsey *et al.,* 2019). Both reports relied on Forest Inventory and Analysis (FIA) and several validated, data-driven modeling tools to provide nationally consistent evaluations of forest carbon trends across the National Forest System (NFS). The Baseline Report applies the Carbon Calculation Tool (CCT) (Smith *et al.*, 2007), which summarizes available FIA data across multiple survey years to estimate forest carbon stocks and changes in stocks at the scale of the national forest from 1990 to 2013. The Baseline Report also provides information on carbon storage in harvested wood products (HWP) for each Forest Service region. The Disturbance Report provides a national forest-scale evaluation of the influences of disturbances and management activities, using the Forest Carbon Management Framework (ForCaMF) (Healey *et al.*, 2014; Raymond *et al.*, 2015; Healey *et al.*, 2016). This report also contains estimates of the long-term relative effects of disturbance and non-disturbance factors on carbon stock change and accumulation, using the Integrated Terrestrial Ecosystem Carbon (InTEC) model (Chen *et al.*, 2000; Zhang *et al.*, 2012). See Box 1 for descriptions of the carbon models used for these analyses. Additional reports, including the most recent Resource Planning Act (RPA) assessment (USDA Forest Service, 2016) and the Northern California Climate Change Vulnerability Assessment Syntheses (EcoAdapt, 2019)Collectively, these reports incorporate advances in data and analytical methods, representing the best available science to provide comprehensive assessments of NFS carbon trends.

1.1 Background

The Mendocino NF, located in the California Northern Coast Ranges, covers approximately 369,602 ha, approximately 299,076 ha of which is forested. California mixed conifer, Western Oak, Douglas-fir, and fir-spruce-mountain hemlock forest types are the most abundant forest types across the Mendocino NF, according to FIA data. The carbon legacy of Mendocino NF and other national forests in the region is tied to the history of both historical Native American management then changes resulting from Euro-American settlement, land management, and disturbances.

Thousands of years before pioneer explorers from the eastern United States entered the area, five Native American peoples lived off its bounty - the Yuki, Nomlaki Wintu, Patwin Wintu, Eastern Pomo, and Northeastern Pomo. Archaeological artifacts and records from more than 1,800 sites have told us a number of things about the distant past of these peoples, but we have much more to learn.

Box 2. Carbon Units. The following table provides a crosswalk among various metric measurements units used in the assessment of carbon stocks and emissions.

Tonnes				Grams		
Multiple	Name	Symbol		Multiple	Name	Symbol
				10^0	Gram	G
				10^3	kilogram	Kg
10^0	tonne	t		10^6	Megagram	Mg
10^3	kilotonne	Kt		10^9	Gigagram	Gg
10^6	Megatonne	Mt		10^{12}	Teragram	Tg
10^9	Gigatonne	Gt		10^{15}	Petagram	Pg
10^{12}	Teratonne	Tt		10^{18}	Exagrame	Eg
10^{15}	Petatonne	Pt		10^{21}	Zettagram	Zg
10^{18}	Exatonne	Et		10^{24}	yottagram	Yg

1 hectare (ha) = 0.01 km^2 = 2.471 acres = 0.00386 mi^2
1 Mg carbon = 1 tonne carbon = 1.1023 short tons (U.S.) carbon
1 General Sherman Sequoia tree = 1,200 Mg (tonnes) carbon
1 Mg carbon mass = 1 tonne carbon mass = 3.67 tonnes CO_2 mass
A typical passenger vehicle emits about 4.6 tonnes CO_2 a year

Between 1850 and 1900, many small sawmills operated within what are now the Mendocino National Forest Boundaries. Mining also played a role in the history of the area. Copper City and Pacific City, now just place names on the map, were mining communities before the turn of the century. Most mining activity was limited to exploration for copper in the late 1800's, completely disappearing before 1900. During World War II, responding to the needs of the war industry, miners re-entered the Forest to do exploratory digging for manganese and chrome.

First set aside as a "forest reserve" by President Roosevelt on February 6, 1907, the Mendocino

NF was originally named the Stony Creek Forest Reserve and later the California National Forest on July 1, 1908. This designation proved to be confusing with relation to the state itself, and President Herbert Hoover renamed it the Mendocino National Forest on July 12, 1932.

Widening markets, expanding transportations systems, and advancing technologies brought varying degrees of material prosperity to the region, but at severe costs to the natural environment (*ibid*). Environmental degradation included eroded hillsides, hydraulic mining pits, silted rivers, toxic tailings, overgrazed range lands, and denuded timberlands *(ibid*.). The legacy of timber harvest and early efforts to restore the forest are visible today, influencing forest age structures, tree composition, and carbon dynamics (Birdsey *et al.*, 2006).

Beginning with the establishment of National Forests and national fire suppression policies in the early 20th century, the Mendocino National Forest experienced effects to its carbon stores from reduced fire on the landscape. An overall increase in stand densities, especially pronounced in drier forest types like California mixed conifer, occurred over this time period.

Meanwhile, timber harvest levels, particularly in the 1950s-1980s, caused concern across the Pacific Northwest over reduction in old-growth forest and wildlife habitat. In 1994, the Northwest Forest Plan was signed, preventing further forest harvest in old growth stands and restricting forest harvest in other areas.

Since then, expanded human incursion into wildlands and increasing effects of climate change have been interacting with the legacy of European fire suppression and increasing the amount of fire, including high severity fire, on the Mendocino National Forest.

2.0 Baseline Carbon Stocks and Flux

2.1 Forest Carbon Stocks and Stock Change

According to results of the Baseline Report (USDA Forest Service, 2015), carbon stocks in the Mendocino NF have remained fairly stable with a potential slight increase from 52.8±11.6 teragrams of carbon (Tg C) in 1990 to 55.6±11.8 Tg C in 2013, a 5.3 percent increase in carbon stocks over this period (Fig. 1). For context, 55.6 Tg C is equivalent to the emissions from approximately 44.4 million passenger vehicles in a year. For context, there were 26 million registered passenger vehicles in the state of California in 2019 (California 2019). With the uncertainty in annual carbon stock estimates, reflected by the 95 percent confidence intervals, it is likely that carbon stocks on the Mendocino NF were stable. It is important to note that the data presented in Figure 1 represents the carbon baseline from 1990 – 2013 and may not be representative of historic baseline conditions. Previous studies that have attempted to reconstruct historic baseline conditions could not do so without a high degree of uncertainty and are overall inconclusive about how they compare to current conditions (Fellows and Goulden, 2008; North et al., 2009; Collins, 2011; McIntyre et al, 2015; Copolleto et al., 2021). It is important to consider both historic and current baseline conditions when evaluating future trends in carbon uptake and storage.

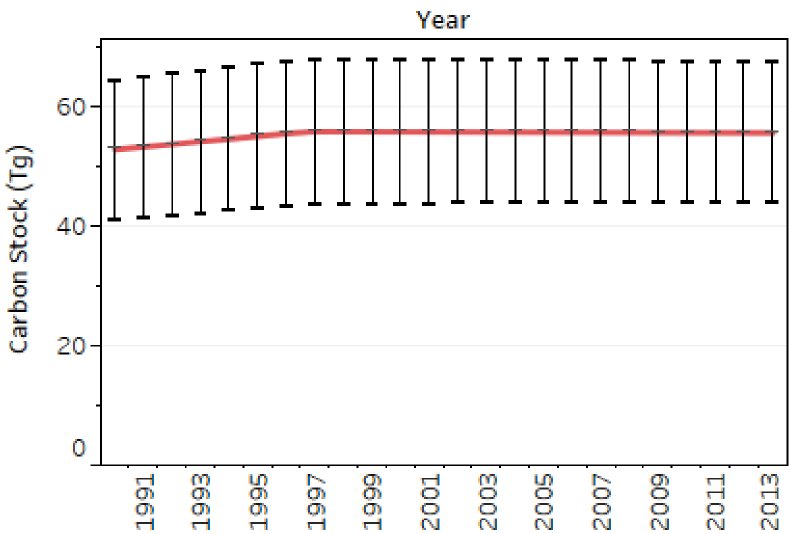

Figure 1. *Total forest carbon stocks (Tg) from 1990 to 2013 for Mendocino National Forest, bounded by 95 percent confidence intervals. Estimated using the CCT model.*

The aboveground portion of live trees, which includes all live woody vegetation at least one inch in diameter (Fig. 2) is the largest carbon pool (as of 2013), storing 43 percent of the forest carbon stocks on the Mendocino NF. About 38.9 percent of forest carbon stocks in the Mendocino NF are stored in the soil carbon contained on the forest floor and in organic material to a depth of one meter (excluding roots). Recently, new methods for measuring soil carbon have found that the amount of carbon stored in soils generally exceeds the estimates derived from using the methods of the CCT model by roughly 12 percent across forests in the United States (Domke *et al.*, 2017).

The annual carbon stock change can be used to evaluate whether a forest is a carbon sink or source in a given year. Carbon stock change is typically reported from the perspective of the atmosphere. A negative value indicates a carbon sink: the forest is absorbing more carbon from the atmosphere (through growth) than it emits (via decomposition, removal, and combustion). A positive value indicates a source: the forest is emitting more carbon than it takes up.

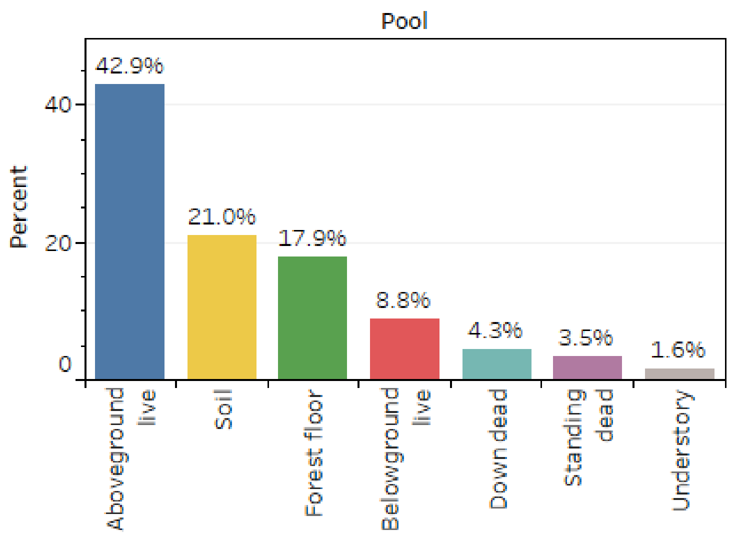

Figure 2. *Percentage of carbon stocks in 2013 in each of the forest carbon pools, for Mendocino National Forest. Estimated using the CCT model.*

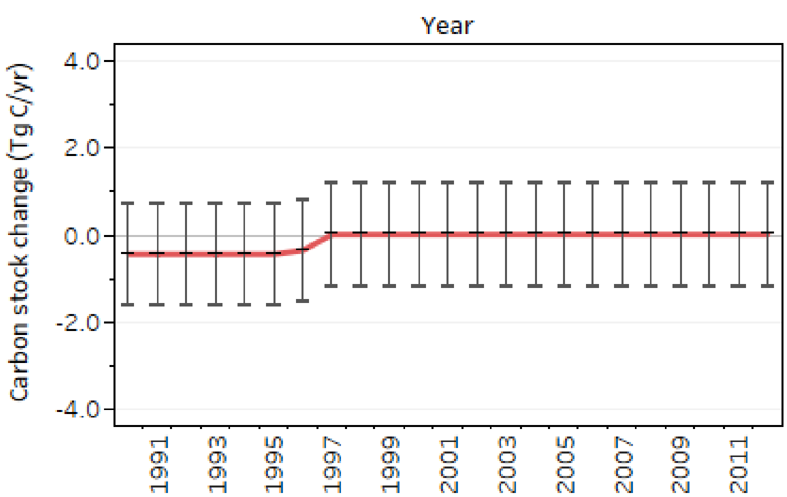

Figure 3. *Carbon stock change (Tg/yr) from 1990 to 2012 for Mendocino National Forest, bounded by 95 percent confidence intervals. A positive value indicates a carbon source, and a negative value indicates a carbon sink. Estimated using the CCT model.*

Annual carbon stock changes on the Mendocino NF were -0.4 ± 1.2 Tg C per year (slight gain) in 1990 and 0.0 ± 1.2 Tg C per year in 2012 (no change) (Fig. 3). The uncertainty between annual estimates can make it difficult to determine whether the forest is a sink or a source in a specific year (i.e., uncertainty bounds overlap zero) (Fig. 3).

Changes in forested area may affect whether forest carbon stocks are increasing or decreasing. The CCT estimates from the Baseline Report are based on FIA data, which may indicate changes in the total forested area from one year to the next. According to the FIA data used to develop these baseline estimates, the forested area on the Mendocino NF increased from 278,353 ha in 1990 to 299,076 ha in 2013, a net change of 20,723 ha.[2] When forestland area increases, total ecosystem carbon stocks typically also increase, indicating a carbon source. The CCT model used inventory data from two different databases. This may have led to inaccurate estimates of changes in forested area, potentially altering the conclusion regarding whether or not forest carbon stocks are increasing or

[2] Forested area used in the CCT model may differ from more recent FIA estimates, as well as from the forested areas used in the other modeling tools.

decreasing, and therefore, whether the national forest is a carbon source or sink (Woodall *et al.*, 2011).

Carbon density, which is an estimate of forest carbon stocks per unit area, can help identify the effects of changing forested area. In the Mendocino NF, carbon density decreased from about 189.8 Megagrams of carbon (Mg C) per ha in 1990 to 185.9 Mg C per ha in 2013 (Fig. 4). This slight decrease in carbon density, only about 2 percent, suggests that total carbon stocks are indeed stable.

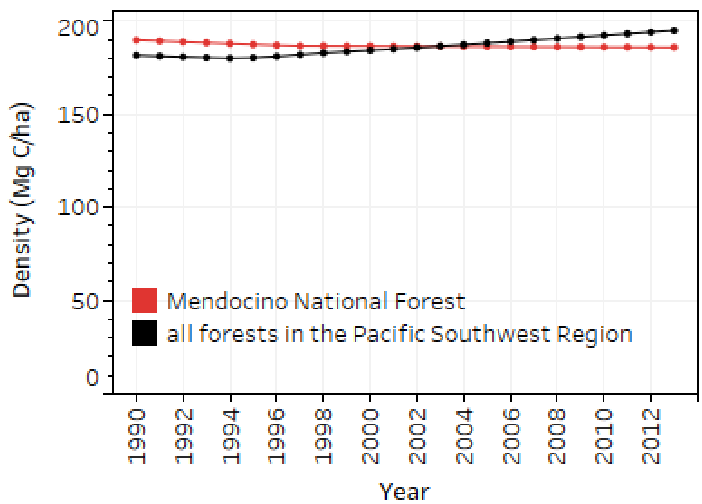

Figure 4. *Carbon stock density (Megagrams per hectare) in the Mendocino National Forest and the average carbon stock density for all forests in the Pacific Southwest Region from 1990 to 2013. Estimated using CCT.*

Carbon density is also useful for comparing trends among units or ownerships with different forest areas. Unlike the Mendocino NF, in aggregate the national forests in the Pacific Southwest Region have experienced slightly increasing carbon densities from 1990 to 2013. Carbon density in the Mendocino NF has been more stable than the average for all national forest units in the Pacific Southwest Region (Fig.4). Differences in carbon density between units may be related to inherent differences in biophysical factors that influence growth and productivity, such as climatic conditions, elevation, and forest types. These differences may also be affected by disturbance and management regimes (see Section 3.0).

2.2 Uncertainty associated with baseline forest carbon estimates

All results reported in this assessment are estimates that are contingent on models, data inputs, assumptions, and uncertainties. Baseline estimates of total carbon stocks and carbon stock change include 95 percent confidence intervals derived using Monte Carlo simulations[3] and shown by the error bars (Figs. 1, 3). These confidence intervals indicate that 19 times out of 20, the carbon stock or stock change for any given year will fall within error bounds. The uncertainties contained in the models, samples, and measurements can exceed 30 percent of the mean at the scale of a national forest, sometimes making it difficult to infer if or how carbon stocks are changing.

[3] A Monte Carlo simulation performs an error analysis by building models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty (e.g., data inputs). It then calculates results over and over, each time using a different set of random values for the probability functions.

The baseline estimates that rely on FIA data include uncertainty associated with sampling error (e.g., area estimates are based on a network of plots, not a census), measurement error (e.g., species identification, data entry errors), and model error (e.g., associated with volume, biomass, and carbon equations, interpolation between sampling designs). As mentioned in Section 2.1, one such model error has resulted from a change in FIA sampling design, which led to an apparent change in forested area. Change in forested area may reflect an actual change in land use due to reforestation or deforestation. However, given that the Mendocino NF have experienced minimal changes in land use or adjustments to the boundaries of the national forests in recent years, the change in forested area incorporated in CCT is more likely a data artefact of altered inventory design and protocols (Woodall *et al.*, 2013).

The inventory design changed from a periodic inventory, in which all plots were sampled in a single year to a standardized, national, annual inventory, in which a proportion of all plots is sampled every year. The older, periodic inventory was conducted differently across states and tended to focus on timberlands with high productivity. Any data gaps identified in the periodic surveys, which were conducted prior to the late 1990s, were filled by assigning average carbon densities calculated from the more complete, later inventories from the respective states (Woodall *et al.*, 2011). The definition of what constitutes forested land also changed between the periodic and annual inventory in some states, which may also have contributed to apparent changes in forested area.

In addition, carbon stock estimates contain sampling error associated with the cycle in which inventory plots are measured. Forest Inventory and Analysis plots are resampled about every 10 years in California, and a full cycle is completed when every plot is measured at least once. However, sampling is designed such that partial inventory cycles provide usable, unbiased samples annually but with higher errors. These baseline estimates may lack some temporal sensitivity, because plots are not resampled every year, and recent disturbances may not be incorporated in the estimates if the disturbed plots have not yet been sampled. Although CCT is linked to a designed sample that allows straightforward error analysis, it is best suited for detecting broader and long-term trends, rather than annual stock changes due to individual disturbance events.

In contrast, the Disturbance Report (Section 3.0) integrates high-resolution, remotely-sensed disturbance data to capture effects of each disturbance event the year it occurred. This report identifies mechanisms that alter carbon stocks and provides information on finer temporal scales. Consequently, discrepancies in results may occur between the Baseline Report and the Disturbance Report (Dugan *et al.*, 2017).

2.3 Carbon in Harvested Wood Products

Although harvest transfers carbon out of the forest ecosystem, most of that carbon is not lost or emitted directly to the atmosphere. Rather, it can be stored in wood products for a variable duration depending on the commodity produced. Wood products can be used in place of other more emission intensive materials, like steel or concrete, and wood-based energy can displace fossil fuel energy, resulting in a substitution effect (Gustavsson *et al.,* 2006; Lippke *et al.,* 2011).

Much of the harvested carbon that is initially transferred out of the forest can also be recovered with time as the affected area regrows.

Carbon accounting for harvested wood products (HWP) contained in the Baseline Report was conducted by incorporating data on harvests on national forests documented in cut-and-sold reports within a production accounting system (Smith *et al.*, 2006; Stockmann et al., 2014). This approach tracks the entire cycle of carbon, from harvest to timber products to primary wood products to disposal. As more commodities are produced and remain in use, the amount of carbon stored in products increases. As more products are discarded, the carbon stored in solid waste disposal sites (landfills, dumps) increases. Products in solid waste disposal sites may continue to store carbon for many decades.

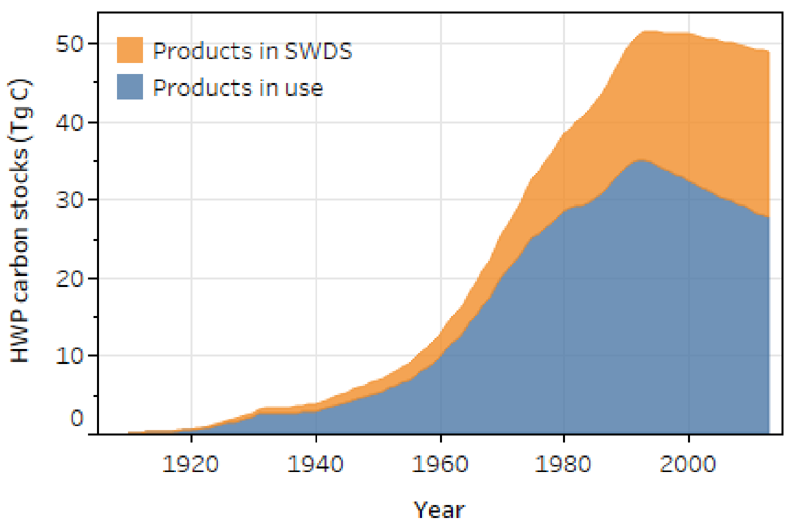

***Figure 5**. Cumulative total carbon (Tg) stored in harvested wood products (HWP) sourced from national forests in the Pacific Southwest Region. Carbon in HWP includes products that are still in use and carbon stored at solid waste disposal sites (SWDS). Estimated using the IPCC production accounting approach.*

In national forests in the Pacific Southwest Region, harvest levels rose in the 1920s before plunging again during the Great Depression. Harvest levels rose again in the 1940s, which caused an increase in carbon storage in HWP (Fig. 5). Timber harvesting and subsequent carbon storage increased rapidly in the 1950s and 1960s. Storage in products and landfills peaked at about 51 Tg C in 1994. However, because of a significant decline in timber harvesting in the late 1990s and early 2000s (to 1940s levels) carbon accumulation in products in use began to decrease. In the Pacific Southwest Region, the contribution of national forest timber harvests to the HWP carbon pool is less than the decay of retired products, causing a net decrease in product-sector carbon stocks. In 2013, the carbon stored in HWP was equivalent to approximately 4.1 percent of total forest carbon storage associated with national forests in the Pacific Southwest Region.

2.4 Uncertainty associated with estimates of carbon in harvested wood products

As with the baseline estimates of ecosystem carbon storage, the analysis of carbon storage in HWP also contains uncertainties. Sources of error that influence the amount of uncertainty in the estimates include: adjustment of historic harvests to modern national forest boundaries; factors used to convert the volume harvested to biomass; the proportion of harvested wood used for different commodities (e.g., paper products, saw logs); product decay rates; and the lack of distinction between methane and CO_2 emissions from landfills. The approach also does not consider the substitution of wood products for emission-intensive materials or the substitution of bioenergy for fossil fuel energy, which can be significant (Gustavsson *et al.,* 2006). The collective effect of uncertainty was assessed using a Monte Carlo approach. Results indicated a ±0.05 percent difference from the mean at the 90 percent confidence level for 2013, suggesting that uncertainty is relatively small at this regional scale (Stockmann et al., 2014).

3.0 Factors Influencing Forest Carbon

3.1 Effects of Disturbance

The Disturbance Report builds on estimates in the Baseline Report by supplementing high-resolution, manually-verified, annual disturbance data from Landsat satellite imagery (Healey *et al.*, 2018). The Landsat imagery was used to detect land cover changes due to disturbances including fires, harvests, insects, and abiotic factors (e.g., wind, ice storms). The resulting disturbance maps indicate that fire was the dominant disturbance type detected on the Mendocino NF from 1990 to 2011, in terms of the total percentage of forested area disturbed over the period (Fig. 6a). According to the satellite imagery, fire affected a moderate area of the forest during this time. In most years, fire affected less than 0.1 percent of the total forested area of the Mendocino NF in any single year from 1990 to 2011, but in total, with major fire years affecting up to 2.9% of the forested area in a given year, about 7.7 percent (approximately 22,854 ha) of the average forested area during this period (295,396 ha) was affected by fire. There was no discernible pattern of increase or decrease over this 21-year period, as large fire years where burned area was high are sporadic. It is also difficult to discern whether disturbances became on average more severe in magnitude over that time interval. Although disturbances varied in proportion of trees removed, they generally removed between 50 to 75 percent of canopy cover (magnitude) (Fig. 6b).

Forest harvest affected no more than 0.2 percent of forested area in any given year, for a total of 1.7% over this time period.

The Forest Carbon Management Framework (ForCaMF) incorporates Landsat disturbance maps summarized in Figure 6, along with FIA data in the Forest Vegetation Simulator (FVS) (Crookston & Dixon, 2005). The FVS is used to develop regionally representative carbon accumulation functions for each combination of forest type, initial carbon density, and disturbance type and severity (including undisturbed) (Raymond *et al.*, 2015). The ForCaMF model then compares the undisturbed scenario with the carbon dynamics associated with the historical disturbances to estimate how much more carbon would be on each national forest if the disturbances and harvests during 1990-2011 had not occurred. ForCaMF simulates the effects of disturbance and management only on non-soil carbon stocks (i.e., vegetation, dead wood, forest floor). Like CCT, ForCaMF results supply 95 percent confidence intervals around estimates derived from a Monte Carlo approach (Healey *et al.*, 2014).

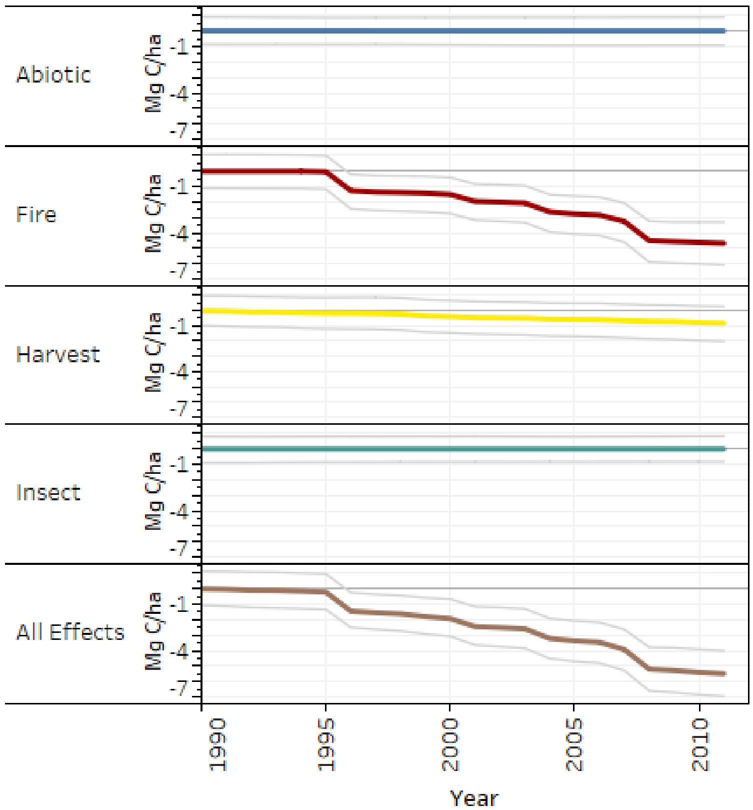

Figure 7. *Lost potential storage of carbon (Megagrams) as a result of disturbance for the period 1990-2011 in Mendocino National Forest. The zero line represents a hypothetical undisturbed scenario. Gray lines indicate 95% confidence intervals. Estimated using the ForCaMF model.*

Fire on the Mendocino NF was the primary disturbance influencing carbon stocks from 1990 to 2011 (Fig. 7). The ForCaMF model indicates that, by 2011, the Mendocino NF contained 4.7 Mg C per ha less non-soil carbon (i.e., vegetation and associated pools) due to fire since 1990, as compared to a hypothetical undisturbed scenario (Fig. 7). As a result, non-soil carbon stocks on the Mendocino NF would have been approximately 3 percent higher in 2011 if fires had not occurred since 1990 (Fig. 8). Non-soil carbon stocks in 2011 on the Mendocino National Forest are estimated to have been 0.6% higher if harvest had not occurred since 1990.

Across all national forests in the Pacific Southwest Region fire has been the most significant disturbance affecting carbon storage since 1990, causing non-soil forest ecosystem carbon stocks

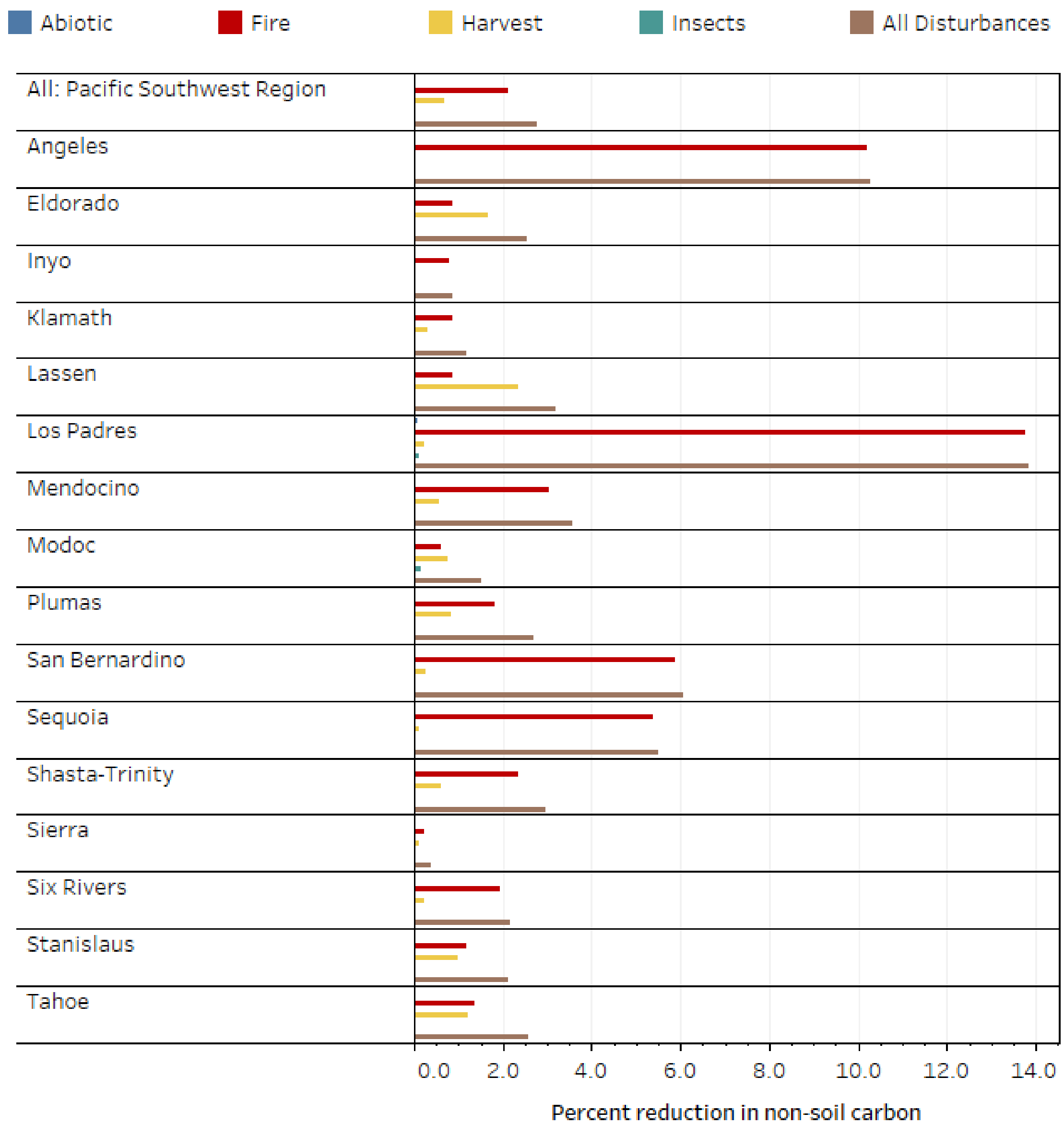

Figure 8. *The degrees to which 2011 carbon storage on each national forest in the Pacific Southwest Region was reduced by disturbance from 1990 to 2011 relative to a hypothetical baseline with no disturbance. The black line indicates the effect of all disturbances types combined. Estimated using disturbance effects from ForCaMF and non-soil carbon stock estimates from CCT.*

to be 2.1 percent lower by 2011 (Fig. 8). Considering all national forests in the Pacific Southwest

Region, between 1990 and 2011, abiotic factors (wind, ice storms) and insects accounted for a negligible amount in comparison, and harvest accounted for a loss of 0.7 percent of non-soil carbon stocks.

The ForCaMF analysis was conducted over a relatively short time relative to forest dynamics. After a forest experiences disturbance, it will usually eventually regrow and recover the carbon removed from the ecosystem in the disturbance. However, several decades may be needed to recover the carbon removed depending on the type of disturbance or harvest (e.g., clear-cut versus partial cut), as well as the conditions prior to the disturbance (e.g., forest type and amount of carbon) (Raymond *et al.*, 2015).

It is also important to note that the time period after 2011, for which compiled data and ForCaMF analysis are not yet available, has seen a dramatic increase in wildfire size and intensity in California. The 2020 fire season alone, broke numerous records. Five of California's six largest fires in modern history burned at the same time, with more than 4 million acres burned across the state, double the previous record. Seventeen of California's largest wildfires since 1932 happened in the two decades between 2000-2020. (Forest Management Task Force, 2021). And as we discussed above using preliminary data, the 2018 and 2020 fire seasons have been strongly affected for the Mendocino National Forest specifically.

The ForCaMF model also does not track carbon stored in harvested wood after it leaves the forest ecosystem. In some cases, removing carbon from forests for human use can result in lower net contributions of GHGs to the atmosphere than if the forest was not managed, when accounting for the carbon stored in wood products, substitution effects, and forest regrowth (Lippke *et al.*, 2011; McKinley *et al.*, 2011; Skog *et al.*, 2014; Dugan *et al.*, 2018). Therefore, the IPCC recognizes wood as a renewable resource that can provide a mitigation benefit to climate change (IPCC, 2000).

ForCaMF helps to identify the biggest local influences on continued carbon storage and puts the recent effects of those influences into perspective. Factors such as stand age, drought, and climate may affect overall carbon change in ways that are independent of disturbance trends. The purpose of the InTEC model was to reconcile recent disturbance impacts with these other factors.

3.2 Effects of Forest Aging

InTEC models the collective effects of forest disturbances and management, aging, mortality, and subsequent regrowth on carbon stocks from 1950 to about 2011. The model uses inventory-derived maps of stand age, Landsat-derived disturbance maps (Fig. 6), and equations describing the relationship between net primary productivity (NPP) and stand age. Stand age serves as a proxy for past disturbances and management activities (Pan *et al.*, 2011b). In the model, when a forested stand is disturbed by a severe, stand-replacing event, the age of the stand resets to zero and the forest begins to regrow. Thus, peaks of stand establishment can indicate stand-replacing disturbance events that subsequently promoted regeneration.

Stand-age distribution for the Mendocino NF derived from 2011 forest inventory data indicates many stands established earlier than 1810 with a few elevated stand establishments between 1900-1960s and the 2000s (Fig. 9a). These periods of elevated stand regeneration came after European settlement began, when forest clearing may have occurred for settlements and timber.

Stands regrow and recover at different rates depending on forest type and site conditions. Forests are generally most productive when they are young to middle age, then productivity peaks and declines or stabilizes as the forest canopy closes and as the stand experiences increased respiration and mortality of older trees (Pregitzer & Euskirchen, 2004; He *et al.*, 2012), as indicated by the in NPP-age curves (Fig. 9b), derived in part from FIA data.

InTEC model results show that the Mendocino NF was accumulating carbon steadily at the start of the analysis in the 1950s until about 1990 (Fig. 10) (positive slope) as a result of regrowth following disturbances and heightened productivity of the young to middle-aged forests (30-60 years old) (Fig. 9b). As stand establishment declined and more stands reached slower growth stages around 2000, the rate of carbon accumulation stagnated and declined (negative slope).

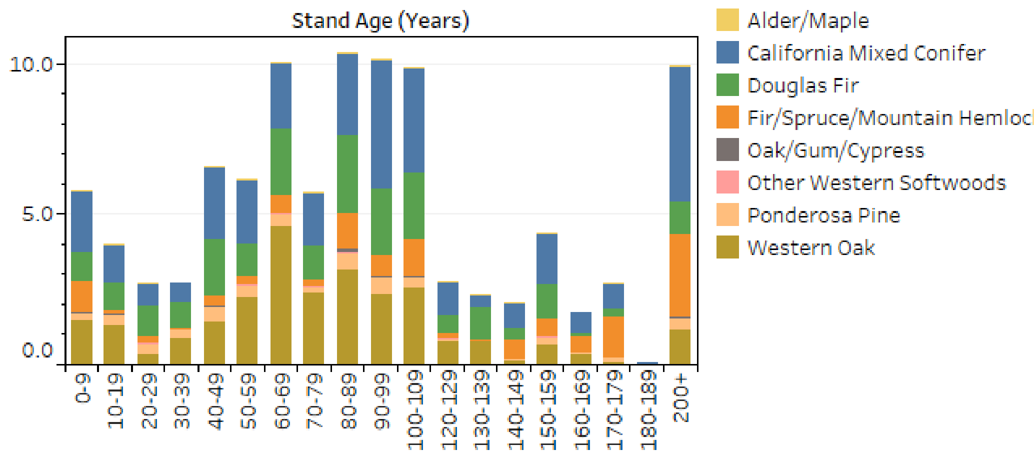

Figure 9. *(a) Stand age distribution in 2011 by forest type group in Mendocino National Forest. Derived from forest inventory data.*

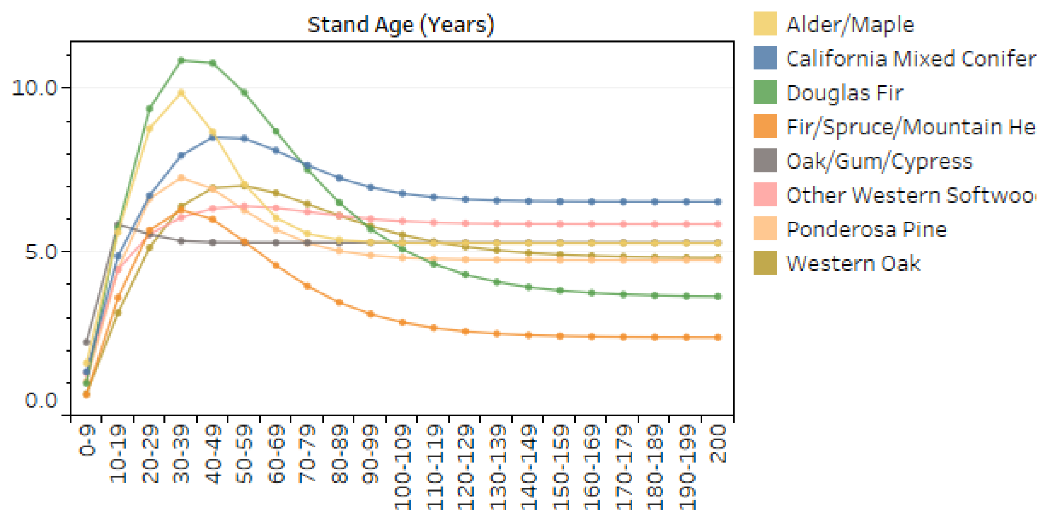

Figure 9. *(b) Net primary productivity-stand age curves by forest type group in Mendocino National Forest. Derived from forest inventory data and He et al. 2012.*

3.3 Effects of Climate and Environment

The InTEC model also isolates the effects of climate (temperature and precipitation), atmospheric CO_2 concentrations, and nitrogen deposition on forest carbon stock change and accumulation. Generally annual precipitation and temperature conditions fluctuate considerably. The modeled effects of variability in temperature and precipitation on carbon stocks has varied from year-to-year, but overall, climate since 1950 had a small negative effect on carbon stocks on the Mendocino NF (Fig. 10). Warmer temperatures can increase forest carbon emissions through enhanced soil microbial activity and higher respiration (Ju *et al.*, 2007; Melillo *et al.*, 2017), but warming temperatures can also reduce soil moisture through increased evapotranspiration, causing lower forest growth (Xu *et al.*, 2013).

In addition to climate, the availability of CO_2 and nitrogen can alter forest growth rates and subsequent carbon uptake and accumulation (Caspersen *et al.*, 2000; Pan *et al.*, 2009). Increased fossil fuel combustion, expansion of agriculture, and urbanization have caused a significant increase in both CO_2 and nitrogen emissions (Chen *et al.*, 2000; Keeling *et al.*, 2009; Zhang *et al.*, 2012). According to the InTEC model, higher CO_2 has consistently had a positive effect on carbon stocks on the Mendocino NF, tracking an increase in atmospheric CO_2 concentrations worldwide (Fig. 10). However, a precise quantification of the magnitude of this CO_2 effect on terrestrial carbon storage is one of the more uncertain factors in ecosystem modeling (Jones *et al.*, 2014; Zhang *et al.*, 2015). Long-term studies examining increased atmospheric CO_2 show that forests initially respond with higher productivity and growth, but the effect is greatly diminished or lost within 5 years in most forests (Zhu *et al.*, 2016). There has been considerable debate regarding the effects of elevated CO_2 on forest growth and biomass accumulation, thus warranting additional study (Körner *et al.*, 2005; Norby *et al.*, 2010; Zhu *et al.*, 2016).

Modeled estimates suggest that overall nitrogen deposition had a positive effect on carbon accumulation on the Mendocino NF (Fig. 10). Like CO_2, the actual magnitude of this effect remains uncertain. Overall, the InTEC model suggests that the effects of CO_2 and nitrogen fertilization offset the declines in carbon accumulation associated with historical disturbance, aging, and regrowth, and climate, until about 2000, at which point InTEC models a declining amount of accumulated carbon from the peak in the 1990s, though still higher than 1950 levels.

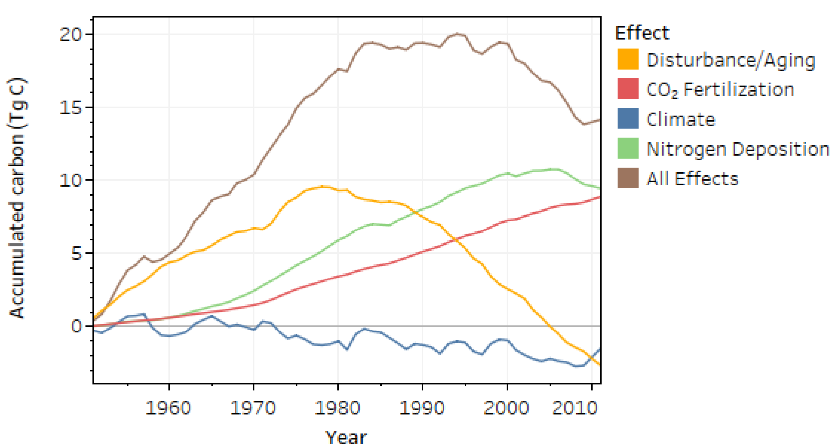

Figure 10. *Accumulated carbon in Mendocino National Forest due to disturbance/aging, climate, nitrogen deposition, CO_2 fertilization, and all factors combined (shown in brown line) for1950–2011, excluding carbon accumulated pre-1950 Estimated using the InTEC model.*

3.4 Uncertainty associated with disturbance effects and environmental factors

As with the baseline estimates, there is also uncertainty associated with estimates of the relative effects of disturbances, aging, and environmental factors on forest carbon trends. For example, omission, commission, and attribution errors may exist in the remotely-sensed disturbance maps used in the ForCaMF and InTEC models. However, these errors are not expected to be significant given that the maps were manually verified, rather than solely derived from automated methods. ForCaMF results may also incorporate errors from the inventory data and the FVS-derived carbon accumulation functions (Raymond *et al.*, 2015). To quantify uncertainties, the ForCaMF model employed a Monte Carlo-based approach to supply 95 percent confidence intervals around estimates (Healey *et al.*, 2014).

Uncertainty analyses such as the Monte Carlo are not commonly conducted for spatially explicit, process-based models like InTEC because of significant computational requirements. However, process-based models are known to have considerable uncertainty, particularly in the parameter values used to represent complex ecosystem processes (Zaehle *et al.*, 2005). InTEC is highly calibrated to FIA data and remotely-sensed observations of disturbance and productivity, so uncertainties in these datasets are also propagated into the InTEC estimates. National-scale sensitivity analyses of InTEC inputs and assumptions (Schimel *et al.*, 2015), as well as calibration with observational datasets (Zhang *et al.*, 2012) suggest that model results produce a reasonable range of estimates of the total effect (e.g., Fig. 10, "All effects"). However, the relative partitioning of the effects of disturbance and non-disturbance factors as well as uncertainties at finer scales (e.g., national forest scale) are likely to be considerably higher.

Results from the ForCaMF and InTEC models may differ substantially from baseline estimates (CCT), given the application of different datasets, modeling approaches, and parameters (Zhang *et al.*, 2012; Dugan *et al.,* 2017). The baseline estimates are almost entirely rooted in empirical forest inventory data, whereas ForCaMF and InTEC involve additional data inputs and modeling complexity beyond summarizing ground data.

4.0 Future Carbon Conditions

4.1 Prospective Forest Aging Effects

The retrospective analyses presented in the previous sections can provide an important basis for understanding how various factors may influence carbon storage in the future. For instance, as of 2011, the forests of the Mendocino NF were mostly middle-aged and older (greater than 80 years) and few stands are young (Fig. 9a). If the Forest were to continue on this aging trajectory, more stands will reach a slower rates of growth stage in coming years and decades (Fig. 9b), potentially causing the rate carbon accumulation to decline and the Forest may continue in a relatively steady state in the future without significant disturbances. Again, the influence of the recent very large wildfires on carbon stocks are not yet fully understood and might alter the trajectory of carbon stocks. Although yield curves indicate that biomass carbon stocks may be approaching maximum levels (Fig. 9b), ecosystem carbon stocks can continue to increase for many decades as dead organic matter and soil carbon stocks continue to accumulate (Luyssaert *et al.*, 2008). Furthermore, while past and present aging trends can inform future conditions, the applicability may be limited, because potential changes in management activities or disturbances could affect future stand age and forest growth rates (Christensen, 2021; Tepley, 2017). Additional monitoring and studies will need to be conducted to determine the change after the major wildfires of 2018 and 2020.

The RPA assessment provides regional projections of forest carbon trends across forestland ownerships in the United States based on a new approach that uses the annual inventory to estimate carbon stocks retrospectively to 1990 and forward to 2060 (Woodall *et al.*, 2015; USDA

Forest Service, 2016). The RPA reference scenario assumes forest area in the U.S. will continue to expand at current rates until 2022, when it will begin to decline due to land use change. However, national forests tend to have higher carbon densities than private lands and may have land management objectives and practices that differ from those on other lands.

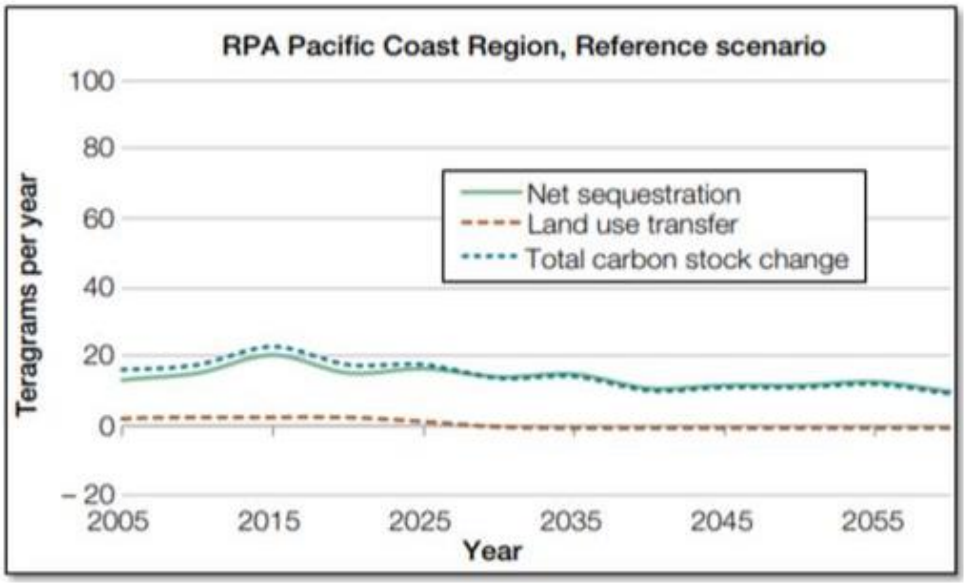

Figure 11. *Projections of forest carbon stock changes in the Pacific Coast Region (equivalent to the boundaries of Pacific Southwest Region and Pacific Northwest and Alaska Regions, but includes all land tenures) for the RPA reference scenario. Net sequestration of forests is the total carbon stock change minus losses associated with land-use change.*

For RPA's Pacific Coast Region (equivalent to a combination of the Forest Service's Pacific Northwest and Pacific Southwest Region boundaries, but includes all land ownerships), projections indicate that the rate of carbon sequestration will decline gradually but will be relatively stable. The trend in total carbon stock change tracks most closely to net sequestration indicating that land-use transfers are not significant in this region (Fig. 11). National forests tend to experience low rates of land-use change, and thus, forest land area is not expected to change substantially within the Mendocino NF in the future. Therefore, on national forest lands, the projected carbon trends may closely resemble the "net sequestration" trend in Fig. 11, which isolates the effects of forest aging, disturbance, mortality, and growth from land-use transfers and indicates a small decline in the rate of net carbon sequestration through 2060.

4.2 Prospective Climate and Environmental Effects

The observational evidence described above and in previous sections highlights the role of natural forest development and succession as the major driver of historic and current forest carbon sequestration that is occurring on the Mendocino NF and elsewhere in across the region.

Climate change introduces additional uncertainty about how forests—and forest carbon sequestration and storage—may change in the future. Climate change causes many direct alterations of the local environment, such as changes in temperature and precipitation, and it has indirect effects on a wide range of ecosystem processes (Vose *et al.*, 2012). Further, disturbance rates are projected to increase with climate change (Vose *et al.*, 2018), an effect exacertabed by non climate stressors such as changes resulting from fire suppresion and human infrastructure

(EcoAdapt, 2019; Hessburg et all, 2019), making it challenging to use past trends to project the effects of disturbance and aging on forest carbon dynamics.

A climate change vulnerability assessment of Northern California (EcoAdapt, 2019; Halofsky et. Al. 2021), which encompasses the Mendocino NF indicates that climate change is expected to cause temperatures to continue to rise in all seasons, increasing mean temperatures by 2.2 to 5.4 degrees C by 2100 (compared to 1951-1980), perhaps even greater in summer maximum temperatures with a greater frequency of heat waves. The increase in mean temperature is projected to be higher in winter than in summer (Grantham, 2018). Mean annual precipitation is projected to decrease between 20 and 34% by 2100 (compared to 1951-1980), especially in the drier season (the wet season is expected to become wetter and warmer and shorter, likely reducing the amount of precipitation received as snow, a form that prolongs the storage of water in these systems, and shortening its residence time). This is expected to increase climatic water deficit (CWD) by 5-16% in the Northern Interior Coast Range. In addition, interannual variability is expected to increase, meaning there will be more years that are either very wet or very dry (EcoAdapt, 2019; Grantham, 2018).

Elevated temperatures may increase soil respiration and reduce soil moisture through increased evapotranspiration, which would negatively affect growth rates and carbon accumulation (Ju *et al.*, 2007; Melillo *et al.*, 2017). Modeled results of recent climate effects using the InTEC model indicate that years with elevated temperatures have generally had a negative effect on carbon uptake in the Mendocino NF (Fig. 10).

These projected climatic changes are expected to impact tree growth, disturbance dynamics, forest establishment and composition of the various ecosystems on the Mendocino National Forest. For example, potential impacts of the projected climatic changes on the mixed conifer and ponderosa pine forests include reduced tree growth, particularly at the southern or xeric edges of species' ranges or climate envelopes and on southern slopes and during drought years, expected to become more frequent and severe in future; increased risk of large-scale forest die-offs following drought events; increased vulnerability to disease and insect outbreaks; increased wildfire size and severity, and changes in post-disturbance dynamics, including potential shifts in species composition or type conversion (for example, from mixed conifer forest to hardwood-dominated systems or to chaparral) (Hilberg, 2019).

While Disturbance Report data for the post-2011 period is not yet available, the wildfire pattern on the Mendocino National Forest most recently, especially in 2018 and 2020, might have a significant impact on carbon stocks and carbon dynamics. have diverged substantially enough from the 1990-2011 baseline discussed above. Preliminary data indicates that the number of acres burnt at high severity in 2020 was more than 10 times that burnt in any other year since 1986, with the exception of 2018. Taken together 2018 and 2020 had more than 5 times more high severity acreage burnt than the 30 years preceding 2018. In all, approximately 88% of the Mendocino's land base have burned between the 2018 Ranch Fire and 2020 August Complex (Figures 12 and 13).

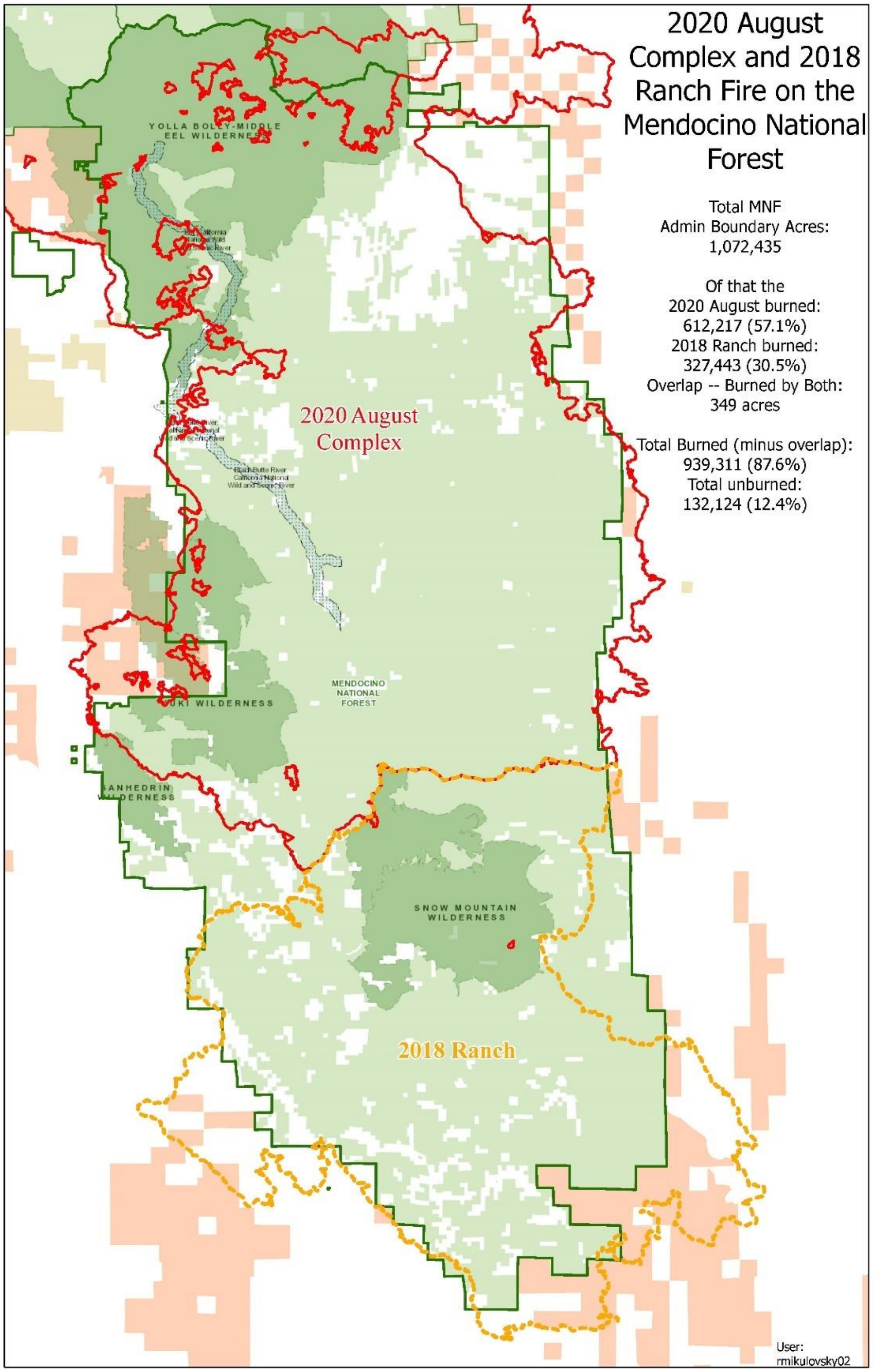

Figure 12. 2020 August Complex and 2018 Ranch Fires with Mendocino National Forest boundary.

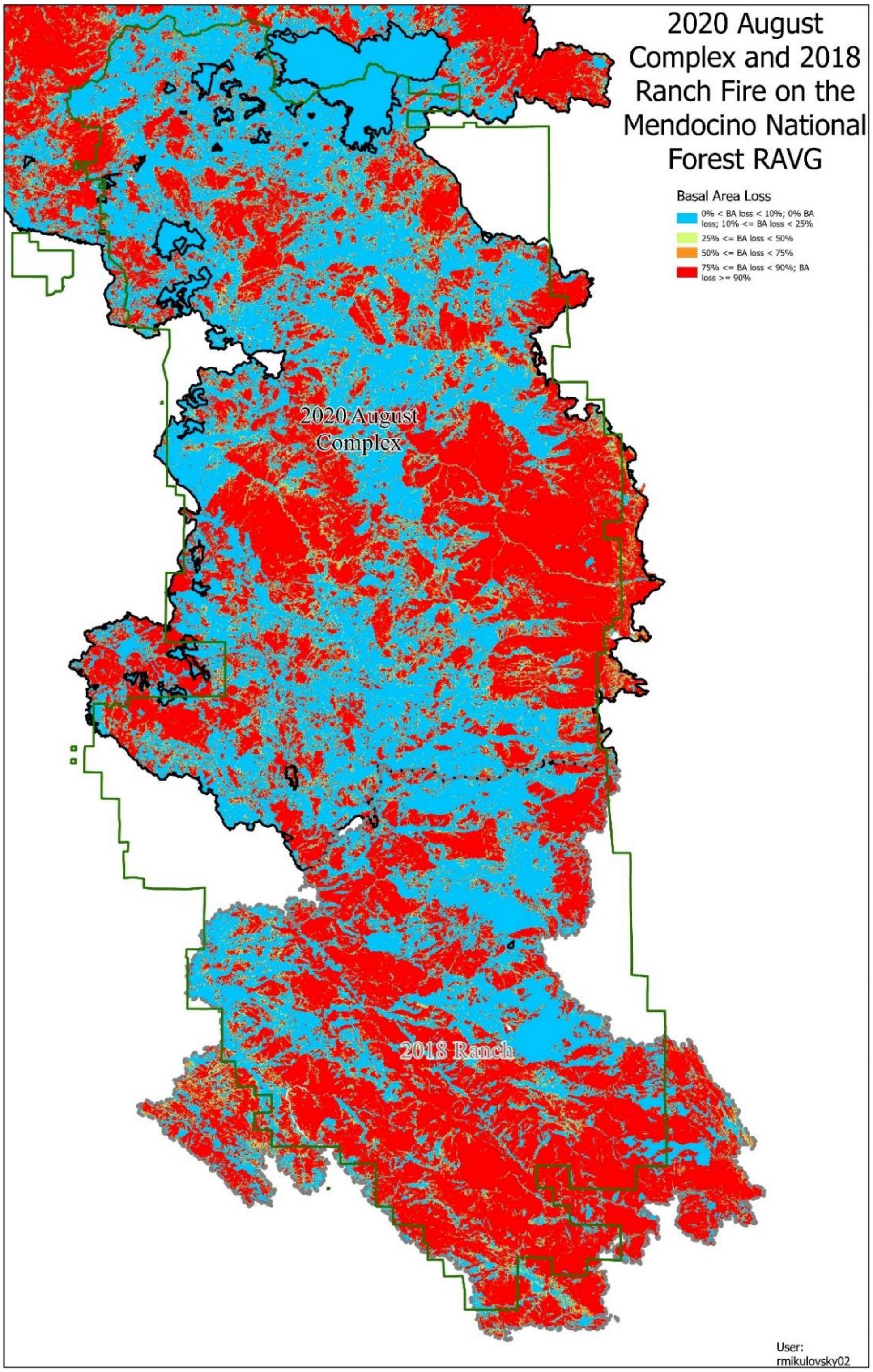

Figure 13. Rapid Assessment of Vegetation Condition after Wildfire (RAVG), showing basal area loss for 2020 August Complex and 2018 Ranch Fires. (USDA Forest Service, 2020)

A particular concern is the increase in the size and severity of fires in recent decades due to an interplay of historical fire suppression and changes in climate. Warmer temperatures, lower and more variable precipitation, with less precipitation occurring as snow, and earlier snow melts, have all been shown as factors in both increasing fire severity and diminishing the pace and success of post-fire recovery. Meanwhile, post-fire changes in vegetation composition and fuel structure, can increase the likelihood of re-burning at high severity. Repeated high severity fires in turn, could drive transitions to non-forested ecosystems in some areas, especially where climatic water deficit increases and/or seed sources are lost. (Hilberg, 2019).

While studies have been performed around the Klamath region, their results can be inferred for the Mendocino due to the similarity in landscapes, fire and disturbance history. In the Klamath mountains region, before fire suppression, fires of variable severity, but tending toward low- and moderate-severity, created high spatial complexity in forest openings, and generally more open-canopy conditions than are typical today. This self-reinforcing heterogeneous pattern enhanced forest resilience but has been replaced by more uniformly dense and layered forests, with more conifers, fewer hardwoods, smaller and fewer openings, and higher fuel connectivity at all levels. Altered fire-vegetation dynamics are evident in the effects of large wildfires that have burned in the Klamath and Southern Cascade Mountains over the last several decades (Hessburg et al, 2019). Though there is no overall trend in total area burned at low, moderate, and high severity in large fires in the Klamath Mountains region, there is a clear trend of increasing fire sizes along with increasing sizes of high-severity burned patches (Skinner et al., 2018). Meanwhile, such stand-replacing fires in dry and mesic forests of the Southern Cascade and Klamath Mountains can promote vegetation shifts from conifers to hardwoods and shrubs, and from forests to shrublands, which are bound to affect future carbon stocks. (Tepley, 2017).

How forests will respond to changes will determine some of the long-term outcomes for carbon storage and fluxes. It is likely that climate-driven changes will impact areas altered most from NRV via a history of logging and decades of fire suppression (Hessburg et al, 2019; ; Hilberg et al, 2019). Drought-stressed trees may be more susceptible to insects and pathogens (Dukes *et al.*, 2009) and other disturbances like fire, which can significantly reduce carbon uptake (Kurz *et al.*, 2008; D'Amato *et al.*, 2011). Climate-driven failures in species establishment further reduce the ability of forests to recover carbon lost after mortality-inducing events or harvests. Although future climate conditions also allow for other future-adapted species to increase, there is greater uncertainty about how well these species will be able to take advantage of new niches that may become available (Hilberg et al, 2019).

Carbon dioxide emissions are projected to increase through 2100 under even the most conservative emission scenarios (IPCC, 2014). Several models, including the InTEC model (Figure 10), project greater increases in forest productivity when the CO_2 fertilization effect is included in modeling (Aber *et al.*, 1995; Ollinger *et al.*, 2008; Pan *et al.*, 2009; Zhang *et al.*, 2012). However, the effect of increasing levels of atmospheric CO_2 on forest productivity is transient and can be limited by the availability of nitrogen and other nutrients (Norby *et al.*, 2010). Productivity increases under elevated CO_2 could be offset by losses from climate-related stress or disturbance.

Given the complex interactions among forest ecosystem processes, disturbance regimes, climate, and nutrients, it is difficult to project how forests and carbon trends will respond to novel future conditions. The effects of future conditions on forest carbon dynamics may change over time. As climate change persists for several decades, critical thresholds may be exceeded, causing unanticipated responses to some variables like increasing temperature and CO_2 concentrations. The effects of changing conditions will almost certainly vary by species and forest type. Some factors may enhance forest growth and carbon uptake, whereas others may hinder the ability of forests to act as a carbon sink, potentially causing various influences to offset each other. Thus, it will be important for forest managers to continue to monitor forest responses to these changes and potentially alter management activities to better enable forests to better adapt to future conditions.

5.0 Summary

Forests on the Mendocino NF between 1990 and 2013 likely maintained stable carbon stocks. Between 1990 and 2013, the negative impacts on carbon stocks caused by disturbances and environmental conditions have been modest and balanced by forest growth. According to satellite imagery, fire has been the most prevalent disturbance detected on the Forest between 1990 and 2011. Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017 (Parks and Abatzoglou, 2020). Forest carbon losses associated with fires between 1990 and 2011 were small compared to the total amount of carbon stored in the Forest, resulting in a loss of about 3 percent of non-soil carbon although wildfires have generally increased in size and severity in recent decades. It is unclear how fires since 2011 have affected this percentage and carbon dynamics.

The biggest influence on current carbon dynamics on the Mendocino NF is the legacy of logging and fire suppression during the 20th century, combined with climatic changes that increase the risk of drought and disturbance impacts like fire size and severity, and forest aging. Most stands on the Mendocino NF were greater than 60 years old in 2013, and the rate of carbon sequestration generally declines as stands age. The potential for increasing impacts from disturbances may slow down or reverse the steady trend of carbon storage on the Mendocino NF in the future but with fire activity since 2013, it is unclear both how much of the NF is currently now in a younger, more vigorously growing early seral stage and also how much of the forest may not fully recover with changes in climate.

Based on the historical analysis of carbon accumulation on the Mendocino NF since 1950, a decline in the rate of carbon accumulation or sequestration has already begun (Fig. 10). Matching projections from the RPA assessment over the entire Pacific Coast, a potential age and disturbance related decline in forest carbon accumulation may be underway (Fig. 11). The State of California's Annual Carbon Report, developed to satisfy the requirements of its Assembly Bill 1504, shows that the period of 2011-2019 may still have a positive net flux in carbon in standing live pools as compared with the 2001-2009 period on the Mendocino National Forest; indicating that the Mendocino remained a carbon sink during that time period (Christensen et al, p. 35 and p. A14). However, with recent large fires, data is not readily available to determine whether this status remains.

Climate and environmental factors, including elevated atmospheric CO_2 and nitrogen deposition, have also influenced carbon accumulation on the Mendocino NF. Recent warmer temperatures and precipitation variability may have stressed forests, causing climate to have a modest negative impact on carbon accumulation in the 2000s. Conversely, increased atmospheric CO_2 and nitrogen deposition may have enhanced growth rates and helped to counteract ecosystem carbon losses due to historical disturbances, aging, and climate.

The effects of future climate conditions are complex and remain uncertain. However, under changing climate and environmental conditions, forests of the Mendocino NF may be increasingly vulnerable to a variety of stressors. The increase of stressors and corresponding changing disturbance dynamics (such as the effects of increasing wildfire severity), underscores the need to monitor annual carbon fluxes and track the stability of existing carbon stocks as forests experience shifting disturbance regimes that may mediate potential long-term ecosystem conversion. These potentially negative effects might be balanced somewhat by the positive effects of longer growing season, greater precipitation, and elevated atmospheric CO_2 concentrations. However, it is difficult to judge how these factors and their interactions will affect future carbon dynamics on the Mendocino NF.

Forested area on the Mendocino NF will be maintained as forest in the foreseeable future, which will allow for a continuation of carbon uptake and storage over the long term. Across the broader region, land conversion for development on private ownerships is a concern (FRAP, 2018) and this activity can cause substantial carbon losses (FAOSTAT, 2013; USDA Forest Service, 2016). The Mendocino NF will continue to have an important role in maintaining the carbon sink, regionally and nationally, for decades to come.

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